Soil, Plant, and Structural Considerations for Surface Barriers in Arid Environments: Application of Results From Studies in the Mojave Desert near Beatty, Nevada

B.J. Andraski and David E. Prudic, U.S. Geological Survey, Carson City, Nevada

INTRODUCTION

The suitability of a waste-burial site depends on hydrologic processes that can affect the near-surface water balance. In addition, the loss of burial trench integrity by erosion and subsidence of trench covers may increase the likelihood of infiltration and percolation, thereby reducing the effectiveness of the site in isolating waste. Although the main components of the water balance may be defined, direct measurements can be difficult, and actual data for specific locations are seldom available. A prevalent assumption is that little or no precipitation will percolate to buried wastes at an arid site. Thick unsaturated zones, which are common to arid regions, are thought to slow water movement and minimize the risk of waste migration to the underlying water table. Thus, reliance is commonly placed on the natural system to isolate contaminants at waste-burial sites in the arid West.

Few data are available to test assumptions about the natural soil-water flow systems at arid sites, and even less is known about how the natural processes are altered by construction of a waste-burial facility. The lack of data is the result of technical complexity of hydraulic characterization of the dry, stony soils, and insufficient field studies that account for the extreme temporal and spatial variations in precipitation, soils, and plants in arid regions. In 1976, the U.S. Geological Survey (USGS) began a long-term study at a waste site in the Mojave Desert. This paper summarizes the findings of ongoing investigations done under natural-site and waste-burial conditions, and discusses how this information may be applied to the design of surface barriers for waste sites in arid environments.

The waste-burial site is in one of the most arid parts of the United States and is about 40 km northeast of Death Valley, near Beatty, Nev. (Figure 1). Precipitation averaged 108 mm/yr during 1981-1992. The water table is 85-115 m below land surface (Fischer, 1992). Sediments are largely alluvial and fluvial deposits (Nichols, 1987). Vegetation is sparse; creosote bush is the dominant species. The waste facility has been used for burial of low-level radioactive waste (1962-1992) and hazardous chemical waste (1970 to present). Burial-trench construction includes excavation of native soil, emplacement of waste, and backfilling with previously stockpiled soil. Only the most recently closed hazardous-waste trench (1991) incorporates a plastic liner in the cover. The surfaces of completed burial trenches and perimeter areas are kept free of vegetation.

FIGURE 1 Location of waste-burial site, Death Valley, and Mojave Desert of southwestern United States.

WATER MOVEMENT THROUGH DEEP UNSATURATED ZONE BENEATH UNDISTURBED, VEGETATED AREA

Field investigations to define the rates and directions of water movement through the deep unsaturated zone beneath an undisturbed, vegetated area began in the early 1980's and continue today. A vertical shaft allows personnel access for instrumentation of the upper 13 m of the unsaturated zone (Fischer, 1992), and additional test holes have been drilled (Prudic, 1994a). Thermocouple psychrometers are used to monitor water pressure and temperature, and a neutron probe is used to measure water content. Soil samples have been analyzed for chloride concentration in pore water (Prudic, 1994a), and water pressure of these samples has been determined using the water-activity meter described by Gee et al. (1992).

Chloride concentrations in pore water were used to estimate the period during which chloride has accumulated in the soil. The distribution of chloride in pore water within the upper 12 m of soils at the site is shown in Figure 2a. These data were determined from core samples collected from test holes (Prudic, 1994a) and from samples collected during excavation of two test trenches. Chloride concentrations at land surface range from 0.05 g/L at test hole UZB-1 to 2 g/L at the east trench. Concentrations are less than 0.5 g/L between the depths of 0.25 and 0.5 m and increase rapidly until the chloride peaks at 6-9 g/L between the depths of 1 and 3 m for test hole IB-1 and for the east and west trenches. Insufficient data are available from UZB-1 to determine a depth of peak concentration. In UZB-1, chloride concentrations decrease to about 0.05 g/L at a depth of about 12 m (Figure 2a) and remain less than 0.05 g/L to the last sampled depth of 85 m. Concentrations at depths greater than 12 m are less than the 0.08 g/L of dissolved chloride in ground water from a nearby well (Prudic, 1994a). The differences in the chloride distribution in the upper 5 m between the sites (Figure 2a) indicates that percolation is not distributed uniformly. Perhaps slight differences in topography or distribution of plants affect the depth of percolation and subsequent distribution of chloride in the soils.

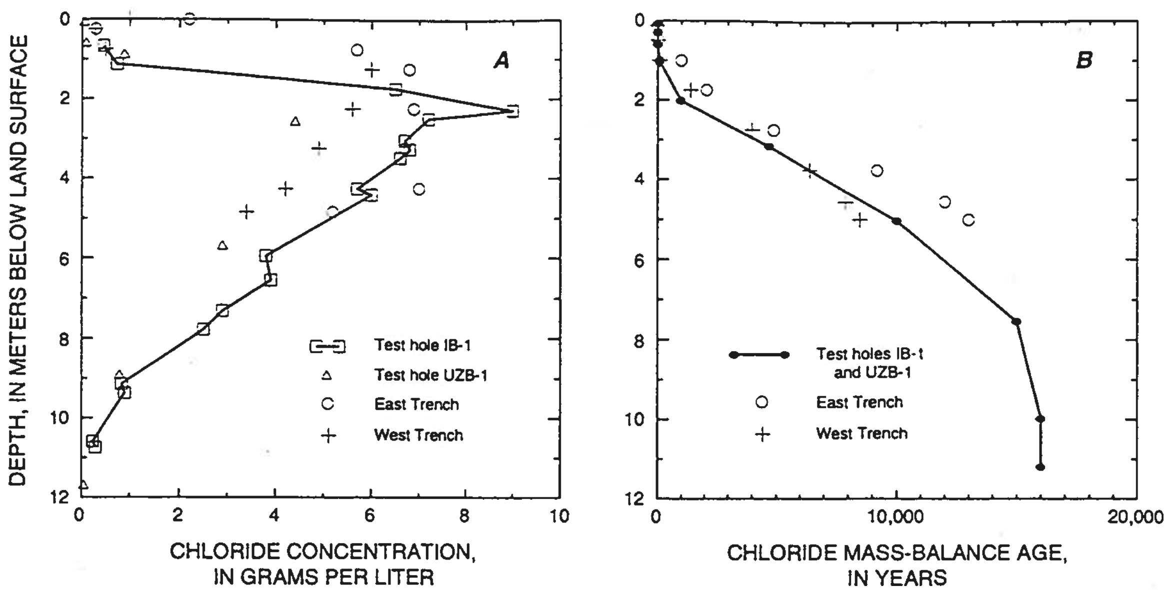

FIGURE 2 Chloride concentrations (a) and estimated chloride-mass balance age (b) for pore water of soil at four locations at study site.

Estimated chloride mass-balance ages of pore water were calculated by dividing the mass of chloride above a given depth by the atmospheric chloride-deposition rate at land surface (Phillips et al., 1988). Estimated ages are only approximate because long-term chloride deposition is unknown. The ages in Figure 2b are based on a chloride-deposition rate of 1.6×10^{-5} g/cm^2/yr. This deposition rate assumes an average precipitation rate of 150 mm/yr and a chloride concentration of 1.1×10^{-6} g/cm^3 for precipitation and dry fallout. This rate is the greater of the two values used by Prudic (1994a) and is greater than the rate of 1.0×10^{-5} g/cm^2/yr reported by Phillips (1994) for the Nevada Test Site, about 40 km southeast of the study site. In the uppermost 0.5 m of soils, estimated ages of pore water are less than 50 years (modern). Below a depth of 1 m, estimated ages increase rapidly. At a depth of 5 m, ages range from about 9,000 years for the west trench to 13,000 years for the east trench. At a depth of 10 m, estimated age of pore water is 16,000 years. Owing to small chloride concentrations below a depth of 10 m, estimated ages increase only 2,000 years between the depths of 10 and about 85 m (Prudic, 1994a). Decreasing the estimated chloride-deposition rate to 8.2×10^{-6} g/cm^2/yr and recalculating results in pore-water ages that are about twice those shown in Figure 2b. This deposition rate is based on a chloride concentration of 0.82×10^{-6} g/cm^3 measured at nearby Yucca Mountain (C.A. Peters, U.S. Geological Survey, written communication, 1992) and a precipitation rate of 10 cm/yr, which more closely approximates present-day conditions. Calculations based on either of the two deposition rates indicate that if the only source of chloride in the soils is from atmospheric deposition, then considerable time is needed to accumulate the quantity of measured chloride.

The low chloride concentrations below 10 m indicate either that the deeper soils were flushed with dilute water in the past or that chloride never accumulated in the soils. The estimated chloride age of 16,000 to 33,000 years at a depth of 10 m approximates the time when the climate in the area was wetter and cooler (Spaulding, 1985). Greater percolation and more frequent flooding of the Amargosa River during this period may have kept salts from accumulating in the soils. Since the end of the wetter period, the soils probably have been drying in response to the arid climate, and percolation of water during the past several thousand years has been limited to the upper 10 m, resulting in an accumulation of salts near the surface.

The lack of percolation below a depth of 10 m is consistent with observed upward water-pressure and vapor-density gradients between the depths of about 12 and 48 m (Prudic, 1994b). Water pressures are less than -360 m (-3.5 MPa) between 3 and 12 m, then increase to -90 m at a depth of 48 m. Hydraulic heads calculated from water pressure (corrected for osmotic pressure) and elevation head are shown in Figure 3a. Water-pressure data are based on psychrometer measurements made on September 16, 1993, and water-activity measurements on core samples collected during drilling of two test holes (UZB-1, November 1992; UZB-2, September 1993). The uncertainty in water pressures determined from water-activity measurements is about ±40 m and from psychrometers is about ±20 m. Considerable scatter appears in the hydraulic head of the upper few meters. The smaller hydraulic heads estimated from core samples near land surface may result from soil drying during drilling or sampling. Nevertheless, hydraulic heads in the upper 50 m are less than the hydraulic head at the water table, indicating a drying trend and upward liquid flow. In addition, vapor density decreases upward from 21.4 $\mu g/cm^3$ at 48 m to 18.6 $\mu g/cm^3$ at 12 m in response to a temperature gradient of 0.06°C/m, indicating upward vapor flow (Prudic, 1994a).

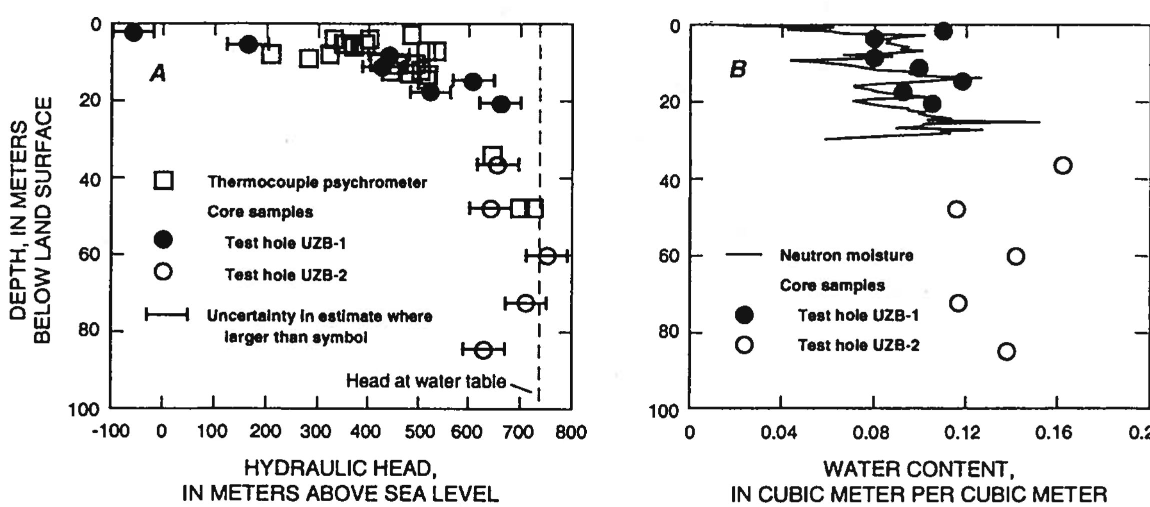

FIGURE 3 Changes in (a) hydraulic head and (b) water content with depth. Heads calculated from psychrometer data and from water-pressure measurements of core samples; water content from core samples and from neutron-moisture probe measurements.

No psychrometers were installed below a depth of 50 m. Hydraulic head estimated from a core sample at 60 m is about equal to that at the water table and head from a sample at a depth of 85 m is less than that at the water table (Figure 3a). Whether the head at 60 m represents a past infiltration event is unknown. Chloride concentrations in the pore water at depths of 48- to 85-m range from 0.04 to 0.05 g/L, about twice as great as the concentrations of 0.02-0.03 g/L determined at depths of 15 m to about 37 m (Prudic, 1994a). Perhaps the greater concentrations at depth represent a previous near-surface accumulation of chloride that percolated downward under wetter climatic conditions.

Core samples collected from test holes UZB-1 and UZB-2 show generally greater water content below a depth of 35 m (Figure 3b). The water content of core samples in the upper 20 m generally corresponds with the water content determined from neutron-moisture measurements made in November 1992. Seasonal changes in water content at the undisturbed, vegetated site have been observed only within the uppermost meter of soils. This interval corresponds to a zone where chloride concentrations are generally low (Figure 2a). Within the zone of higher chloride concentrations, water content is not measurably changing, but water pressures, temperatures, and vapor densities change seasonally (Fischer, 1992).

EVALUATION OF PROCESSES UNDER WASTE-BURIAL CONDITIONS

The USGS test-trench studies, which began in September 1987, combine field and laboratory experiments to define and evaluate quantitatively the interacting factors and processes that can affect waste isolation. Three disturbed sites were established to simulate burial operations at the waste facility: two nonvegetated test trenches and one profile of undisturbed soil where vegetation was removed (Figure 4) (Andraski, 1990). Herbicide keeps the disturbed sites free of vegetation. The effects of disturbance on the water balance are evaluated in terms of observed differences between data collected at the undisturbed, vegetated site and data collected at the disturbed sites. Erosion of the trench covers is estimated by measuring the distance between the top of monitoring pins and the trench surface. Subsidence is determined by measuring the elevation of monitoring pins and plates with a rod and level. Meteorological data are collected by an automated weather station (Wood and Andraski, 1995).

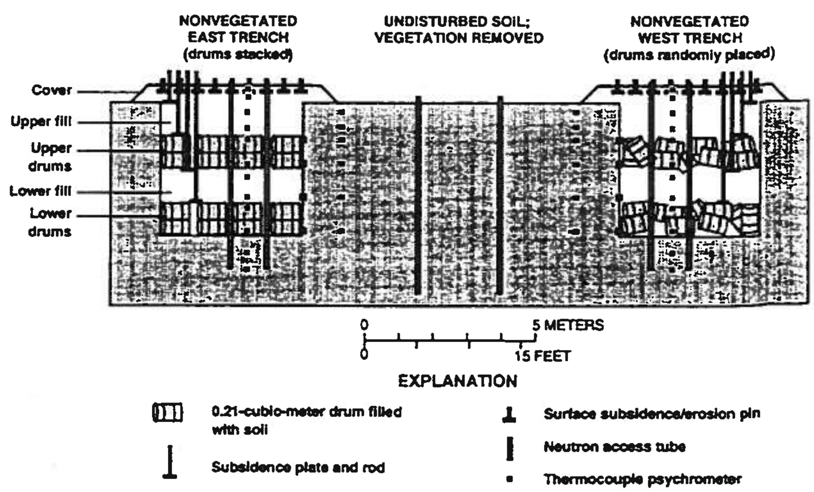

FIGURE 4 General design and instrumentation of three disturbed sites.

Precipitation and cumulative changes in water storage greatly varied during the first 5 years of concurrent monitoring at the four sites (Figures 5a,b). Continual monitoring of nonvegetated soil began in September 1988. Annual water-year precipitation (October through September) ranged from 14 mm (1988-1989) to 162 mm (1987-1988). Storage increases following precipitation were typically greatest for undisturbed soil. During spring and summer, rates of water depletion were greatest for vegetated soil. Even under conditions of extreme aridity (14 and 32 mm of precipitation in 1989 and 1990, respectively), storage values for the three disturbed sites remained greater than those measured initially. Storage values typically were greatest for nonvegetated soil.

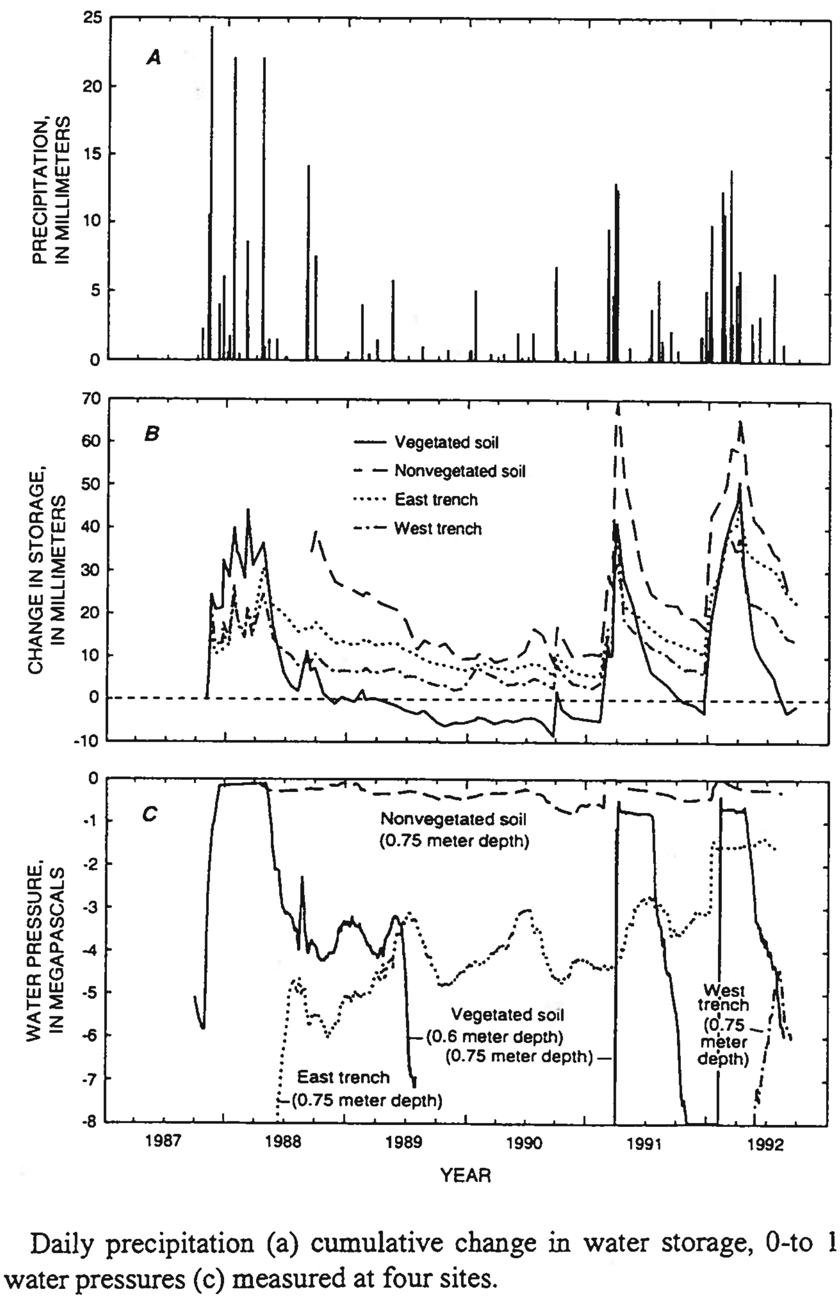

FIGURE 5 Daily precipitation (a) cumulative change in water storage, 0-to 1.25-m depth (b), and daily water pressures (c) measured at four sites.

Water-pressure data illustrate some of the differences in the rates and depths of water accumulation and depletion among the four sites (Figure 5c). Concurrent monitoring at the four sites began in April 1988. Rapid percolation for the undisturbed soils, both vegetated and nonvegetated, resulted in high water pressures during the springs of 1988, 1991, and 1992. Pressures for the east trench show that the wetting front did not reach the 0.75-m depth until June 1988, and pressures for the west trench show that the wetting front did not reach that depth until June 1992. More rapid and deeper percolation in undisturbed soil resulted in smaller evaporative losses. For the trenches, a greater quantity of rock fragments and greater initial water content for the cover of the east trench retarded evaporation and enhanced internal drainage [rock fragments (kg/kg): east = 0.45, west = 0.23; water content (m^3/m^3): east = 0.036, west = 0.021]. Water pressures for vegetated soil show substantial decreases due to water uptake by plants (Figure 5c). Water pressure for vegetated soil (0.6-m depth) decreased to values outside the psychrometer's calibration range between August 1989 and January 1991; this psychrometer was replaced by one at a 0.75-m depth in January 1991.

Although plants have a significant effect on the water balance, the potential for deep percolation also is influenced by soil properties (Gee et al., 1994). Hydraulic properties and their vertical variations in the upper 5 m of soil and trench fill at the site were measured over a water-content range that is representative of arid conditions, but is seldom studied (Andraski, 1996). In contrast to the native soil profile, vertical (layer to layer) variability for trench fill was negligible. Hydraulic characteristics for the two uppermost soil layers (referred to hereafter as layer 1 and 2, respectively) and the trench fill are shown in Figure 6. Water-retention functions were calculated using the Rossi and Nimmo (1994) model. Unsaturated hydraulic conductivity (K_l) was calculated using the Mualem (1976) model, and isothermal vapor conductivity (K_v) was calculated as described by Fayer, Rockhold, and Campbell, (1992). The -1.5-MPa pressure-plate data were omitted from the analysis because water-activity measurements showed that the actual pressures were significantly greater than the expected -1.5-MPa value. The data indicate that use of standard -1.5-MPa pressure-plate data, which commonly serve as the lower limit of retention measurements, can lead to significant errors in the description of hydraulic properties and prediction of water flow in dry soils.

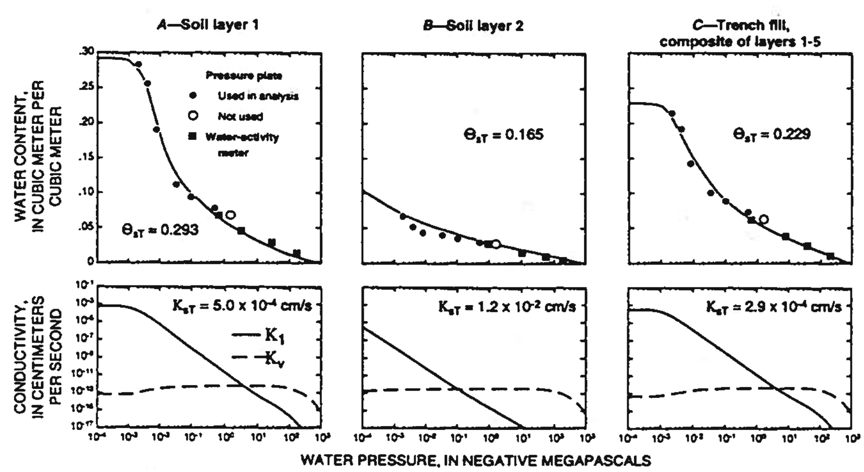

FIGURE 6 Hydraulic properties of soil layers 1(a) and 2(b), and trench fill (c). θ_{sT} is saturated water content; K_{sT}, K_l, and K_v are saturated -, unsaturated-, and isothermal-vapor conductivity, respectively.

The textural difference between soil layer 1 (loamy sand) and layer 2 (gravelly sand) is reflected by their hydraulic properties (Figures 6a,b) and is an important factor in the water balance of the undisturbed soils. Soil layer 1 is about 0.75 m thick, and layer 2 is about 1 m thick. Except for water-pressure values near zero, K_l values for soil layer 1 are greater than those for layer 2. Lower K_l for layer 2 impedes movement out of layer 1. At saturation, layer 1 has the capacity to store 220 mm of water, or about twice the annual average precipitation (108 mm).

Backfilling with the dry fill (< -8 MPa) produced by trench construction, at least initially, will increase the importance of vapor flow in the fill (Figure 6c). As shown by data in Figure 5, however, depending on specific but commonly transient conditions, the relative importance of vapor and liquid flow may differ dramatically. Unlike the native soil profile, the fill provides no textural stratification to impede deep percolation of infiltrated water.

Changes in the structural integrity of trench covers through erosion or subsidence can reduce the waste-isolation potential of a burial site. No measurable soil loss was observed for the east trench, but soil loss for the west trench totaled about 9 mm during the first 5 years of monitoring (Figure 7a). Greater soil loss for the west trench may be attributed to fewer rock fragments in the near surface. Most of the soil loss appeared to be due to deflation. During November and December 1987, two periods of high winds occurred during which hourly average windspeeds of 8-14 m/s persisted for 16 h or more. Nearly 55 percent of total soil loss for the west trench occurred during this time. The decreased rate of soil loss with time for the west trench may be due to increased surface armoring by rock fragments and also surface crusting, which occurs in response to wetting and drying cycles. Data for the east trench indicate a general trend of increased surface elevation with time. This trend may be due to deposition of eolian material (McFadden, Wells, and Jercinovich, 1987) or to the development of vesicular soil structure, which is induced by wetting and drying cycles (Miller, 1971).

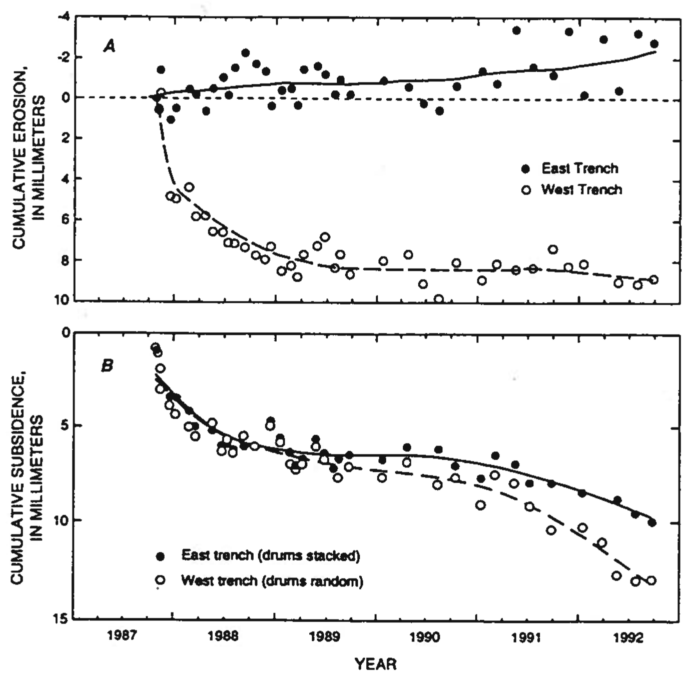

FIGURE 7 Cumulative erosion data (a) and subsidence data (b) measured since October 1987 and trend lines for east and west trenches.

General trends in subsidence were similar for the two test trenches (Figure 7b). During the first year following trench construction, differences between the east trench, where drums were stacked, and the west trench, where drums were randomly placed, were negligible. Subsidence measured during the first year probably represents the natural settling of the uncompacted fill material in response to precipitation and freeze-thaw cycles. During 1990-1992, effects of drum placement became evident, with greater subsidence for the trench where drums were randomly placed. Aside from drum placement effects, rates of subsidence appeared to be correlated with precipitation and concomitant increases in water storage and percolation within the trench cover and upper fill.

APPLICATION TO DESIGN OF BARRIERS FOR LONG-TERM ISOLATION

Investigations at the Mojave Desert site show that, even under extremely arid conditions, the interactive effects of climate, soils, and plants must be considered in the design of surface barriers for long-term waste isolation. The episodic precipitation patterns common to arid regions show the importance of multiple-year field studies. Comprehensive laboratory studies are needed for evaluating the factors and processes controlling waste isolation at arid sites.

Ongoing investigations indicate that, under present climatic conditions, the natural soil-plant system effectively limits the potential for deep percolation. The stratified soil profile, in combination with native plants, provides for rapid infiltration, which reduces runoff; limited depth of percolation; high storage capacity for infiltrated water; and effective seasonal depletion of water accumulated in the root zone. Thus, the natural soil-plant system provides an excellent model for design of surface barriers intended to limit deep percolation and transport of soluble contaminants to ground water in an arid environment.

Construction of burial trenches and elimination of native vegetation markedly alter the natural water balance. In the absence of vegetation, infiltrated water accumulates and continues to percolate downward. Unlike the native soil profile, however, the homogeneous trench fill provides no stratification to impede deep percolation. Thus, changes to the natural site environment may increase the potential for transport of buried waste.

Preliminary evidence indicates that gas flow though the thick unsaturated zone and in the dry backfill potentially may serve as an important contaminant-release pathway at an arid site. The potential magnitude for contaminant transport by this process needs to be considered in the design of arid waste-burial and monitoring systems.

Greater rock-fragment concentration in the near surface of trench covers resulted in greater accumulation of infiltrated water and decreased erosion. Incorporation of this factor into barrier design may enhance vegetation establishment and control erosion.

Effects of drum placement (stacked versus random) on trench cover subsidence were not observed until the third year of monitoring, when subsidence became greater for the trench where drums were placed randomly. Rates of subsidence appear to be correlated with precipitation and concomitant increases in water storage in the trench fill. Establishment of plants on trench covers may minimize cumulative subsidence by reducing water accumulation in trench fill, which, in turn, will reduce the physical load on waste buried below.

Continued long-term monitoring at the Mojave Desert site is critical to documenting how factors and processes controlling waste isolation may change with time. Data from the site provides a much needed, long-term benchmark against which short-term data from other arid sites can be compared. The data base and facilities at the site provide a foundation upon which to build collaborative efforts to further our understanding of hydrologic processes in arid environments. Results show that native plants are extremely important in minimizing deep percolation. Natural revegetation processes at arid sites may be extremely slow, however, and studies to develop strategies for establishment of native vegetation on trench covers are needed. To date, studies at the Mojave Desert site have focused on present-day climatic conditions. Additional study is needed to evaluate how the long-term waste isolation potential of the site might change under wetter climatic conditions.

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BARRIER TECHNOLOGIES
for
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Summary of a Workshop

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